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# Asian climate change under 1.5−4 °C warming targets

XU Ying[a], ZHOU Bo-Tao[a,b,*], WU Jie[c,d], HAN Zhen-Yu[a], ZHANG Yong-Xiang[a], WU Jia[a]

[a] National Climate Center, China Meteorological Administration, Beijing 100081, China
[b] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044, China
[c] Climate Change Research Center, Institute of Atmospheric Sciences, Chinese Academy of Sciences, Beijing 100029, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

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**Abstract**

Based on simulations of 18 CMIP5 models under three RCP scenarios, this article investigates changes in mean temperature and precipitation and their extremes over Asia in the context of global warming targets of 1.5−4 °C, and further compares the differences between 1.5 °C and 2 °C targets. Results show that relative to the pre-industrial era, the mean temperature over Asia increases by 2.3 °C, 3.0 °C, 4.6 °C, and 6.0 °C at warming targets of 1.5 °C, 2 °C, 3 °C, and 4 °C, respectively, with stronger warming in high latitudes than in low latitudes. The corresponding enhancement in mean precipitation over the entire Asian region is 4.4%, 5.8%, 10.2%, and 13.0%, with significant regional differences. In addition, an increase in warm extremes, a decrease in cold extremes, and a strengthening in the variability of amounts of extreme precipitation are projected. Under the 1.5 °C target, compared with the climate under the 2 °C target, the mean temperature will be lower by 0.5−1 °C over Asia; the mean precipitation will be less by 5%−20% over most of Asia, but will be greater by about 10%−15% over West Asia and western South Asia; extreme high temperatures will be uniformly cooler throughout the Asian region, and the warming in extreme low temperatures will decrease significantly in high latitudes of Asia; extreme precipitation will be weaker over most of Asia but will be stronger over West Asia and western South Asia. Under the 1.5 °C and 2 °C warming targets, the probability of very hot weather (anomalies greater than 1σ, σ is standard deviation), extremely hot weather (anomalies greater than 3σ), and extremely heavy precipitation (anomalies greater than 3σ) occurring will increase by at least once, 10%, and 10%, respectively, compared to the reference period (1861−1900).

*Keywords:* Global climate model; CMIP5; Warming target; Climate extreme; Climate change

## 1. Introduction

On December 12, 2015, the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change reached a new accord, the Paris Agreement. This Agreement stipulates a long-term temperature rise threshold with the aim of strengthening the global response to the threat of climate change by maintaining the rise in global temperature this century to well below 2 °C above pre-industrial levels and to pursue efforts to limit this even further to 1.5 °C. This signifies a new stage in international action against climate change.

The IPCC Second Assessment Report (IPCC, 1995) revealed that the risk of climate change will significantly increase if the globally averaged temperature rises by 2 °C with respect to the preindustrial ear. On this basis, in 1996 the European Union proposed a 2 °C warming target. Since then,

* Corresponding author. National Climate Center, China Meteorological Administration, Beijing 100081, China.
*E-mail address:* zhoubt@cma.gov.cn (ZHOU B.-T.).

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the scientific community has conducted numerous studies on global climate change and the resulting impacts and risks under different warming targets (thresholds). The latest finding in the Fifth Assessment Report (AR5) of the IPCC (2014) indicates that a warming of 1–2 °C above pre-industrial levels would severely impact food production, water resources, and ecosystems, in addition to posing a moderate-to high-risk to human and natural systems. However, the risk of these occurrences would be high or very high under a global temperature rise of 4 °C or more.

A study of allowable $CO_2$ emissions based on regional and impact-related climate targets (Seneviratne et al., 2016) also shows that limiting the global temperature rise to 2 °C above pre-industrial levels would not satisfy requirements in many regions. For example, the average temperature in the Mediterranean region would increase by 3.4 °C under a global 2 °C warming target. To maintain temperatures over the Mediterranean region to a rise of 2 °C, it would thus be necessary to limit global increases to 1.4 °C. In addition, a 2 °C global mean temperature would cause a local temperature increase of 6 °C in the Arctic, and to control this to a limit of 2 °C the mean global rise would need to be maintained at lower than 0.6 °C. Schleussner et al. (2016) compared the impacts of climate change under 1.5 °C and 2 °C warming thresholds on coral, precipitation, agriculture, and sea level rise and found a large discrepancy between the impacts associated with the two conditions.

Mitchell et al. (2016) stated that the choice between determining a warming target of 1.5 °C or 2 °C should be based on further in-depth scientific analysis. However, as there is currently a lack of research on this issue, it is now essential to study the characteristics of global and regional climate change under a warming threshold of 1.5 °C. To date, studies concerning warming targets of 2–4 °C have been conducted in China. For instance, based on the CMIP3 analysis, Jiang et al. (2009) and Jiang and Fu (2012) indicated that the temperature increase in China would be greater in the north than in the south, and would be larger in winter than in other seasons under the 2 °C target. Lang and Sui (2013) further used a regional climate model driven by the global climate model to examine changes of mean and extreme climate in China; their results also showed a gradual enhancement of the temperature rise from the south to the north. Moreover, the annual temperature rise over China would be 0.6 °C, greater than the global mean, and there would be a widespread increase/decrease in warm/cold extremes, and an intensification of precipitation extremes with large spatial differences. Using the CMIP5 results, Zhang (2012) and Zhang et al. (2013) analyzed the change in global and China's surface air temperature under the 2 °C target. Furthermore, Chen et al. (2015) investigated the change in 27 climate extreme indices over China under 2 °C, 3 °C, and 4 °C targets, and Guo et al. (2016a, 2016b) examined the change in extreme precipitation and heat waves over China under 1.5–5 °C targets. However, most of these studies have focused on 2–4 °C warming targets (only slight attention has been paid to the 1.5 °C warming threshold) and have focused solely on China rather than the entire Asian region. Therefore, to provide further information, this study aims to use CMIP5 simulation results to explore Asian climate change under 1.5–4 °C warming targets.

## 2. Data and methods

The outputs from 18 CMIP5 models, each of which produced simulations for 1861–2010 and for RCP2.6, RCP4.5, and RCP8.5 (Taylor et al., 2012) are employed in this study; basic information for these models is listed in Table 1, and more details can be found at http://cmip-pcmdi.llnl.gov/cmip5/. To facilitate analysis, all model data were interpolated to 1 × 1° grid.

The target region for analysis is the whole of Asia. To understand the response of climate to global warming thresholds in different regions of Asia, we divided Asia into the six sub-regions used in the AR5 (IPCC, 2013): North Asia (NAS), Central Asia (CAS), East Asia (EAS), West Asia (WAS), South Asia (SAS), and Southeast Asia (SEAS).

The warming thresholds in this study are relative to the pre-industrial climate, and the years 1861–1900 are selected for use as the reference period and to calculate the years in which global temperature rises would reach 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds under the various RCP scenarios (Table 2). The number of models (54 samples regardless of the scenarios) is 41, 33, 20, and 11 respectively for 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds under three RCP scenarios.

The extreme indices are listed in Table 3. The definition of changes in mean and extreme climate follows that determined by Hansen et al. (2012). Taking temperature as an example, when the climate anomaly relative to the reference period is within $\pm 0.43\sigma$ ($\sigma$ is standard deviation) during a certain time period, it is considered to be normal. If the anomaly is larger

Table 1
Basic information for 18 CMIP5 models.

| Model | Affiliation and country | Resolution | Model | Affiliation and country | Resolution |
|---|---|---|---|---|---|
| BCC-CSM1.1 | BCC, China | 128 × 64 | IPSL-CM5A-LR | IPSL, France | 96 × 96 |
| BNU-ESM | GCESS, China | 128 × 64 | IPSL-CM5A-MR | IPSL, France | 144 × 143 |
| CanESM2 | CCCMA, Canada | 128 × 64 | MIROC5 | MIROC, Japan | 256 × 128 |
| CCSM4 | NCAR, America | 288 × 192 | MIROC-ESM | MIROC, Japan | 128 × 64 |
| CNRM-CM5 | CNRM-CERFACS, France | 256 × 128 | MIROC-ESM-CHEM | MIROC, Japan | 128 × 64 |
| CSIRO-Mk3-6-0 | CSIRO-QCCCE, Australia | 192 × 96 | MPI-ESM-LR | MPI-M, Germany | 192 × 96 |
| GFDL-ESM2G | NOAA GFDL, America | 144 × 90 | MPI-ESM-MR | MPI-M, Germany | 192 × 96 |
| GFDL-ESM2M | NOAA GFDL, America | 144 × 90 | MRI-CGCM3 | MRI, Japan | 320 × 160 |
| HadGEM2-ES | MOHC, UK | 192 × 145 | NorESM1-M | NCC, Norway | 144 × 96 |

Table 2
Years in which global surface temperatures relative to the pre-industrial era will reach particular thresholds, as indicated by multimodel ensemble simulation.

| Scenario | 1.5 °C | 2 °C | 3 °C | 4 °C |
|---|---|---|---|---|
| RCP2.6 | 2028 (2012−2044) | × | × | × |
| RCP4.5 | 2028 (2014−2050) | 2048 (2030−2068) | × | × |
| RCP8.5 | 2024 (2012−2041) | 2039 (2027−2055) | 2061 (2046−2081) | 2081 (2066−2095) |

Table 3
Definitions used in temperature and precipitation extreme indices.

| Index | Abbreviation | Definition | Unit |
|---|---|---|---|
| Hottest day | TXx | Maximum of daily maximum temperature | °C |
| Coldest night | TNn | Minimum of daily minimum temperature | °C |
| Very wet day precipitation | R95p | Annual total precipitation when daily precipitation exceeds the 95th percentile of wet-day precipitation | mm |
| Maximum consecutive 5-day precipitation | RX5day | Annual maximum consecutive 5-day precipitation | mm |

(smaller) than $+0.43\sigma$ ($-0.43\sigma$), it is considered to be hot (cold), and anomalies greater (less) than $+1\sigma$ ($-1\sigma$) and $+3\sigma$ ($-3\sigma$) are defined as very hot (very cold) and extremely hot (extremely cold), respectively.

## 3. Results

### 3.1. Changes in temperature and precipitation under different warming targets

Fig. 1 shows the changes in mean temperature and precipitation over Asia and the six sub-regions. It can be seen in Fig. 1a that corresponding to warming thresholds of 1.5 °C, 2 °C, 3 °C, and 4 °C, the temperature over Asia will increase by 2.3 °C, 3.0 °C, 4.6 °C, and 6.0 °C, respectively, compared to the pre-industrial era; these temperatures are all greater than global averages. Furthermore, this increase is widespread across the sub-regions. The greatest change appears in NAS with an increasing amplitude of 2.7 °C under the 1.5 °C threshold and further to 7.0 °C under the 4 °C threshold. The smallest change occurs in SEAS, with a value of 1.5 °C and 4.4 °C under the 1.5 °C and 4 °C thresholds, respectively. Generally, as the global warming threshold becomes higher, there is a greater increase in Asian temperature. In addition, the response to global warming is stronger in high latitudes than in mid-low latitudes, and the spread of the projection is the largest in NAS as indicated by the black line.

For mean precipitation (Fig. 1b), increases of 4.4%, 5.8%, 10.2%, and 13% are projected over Asia in response to 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds, respectively. However, the change in precipitation is not uniform across the region. For instance, under the 1.5 °C threshold, there is a greater increase in precipitation in NAS (9%), followed by CAS (5%), SAS (4%), and EAS (3%), but there is no appreciable change in WAS (0.1%) and SEAS (0.2%). Under the 2 °C threshold, the projected increase of precipitation is 12%, 7%, 4%, and 4% in NAS, SAS, EAS, and CAS, respectively, whereas precipitation shows little change in SEAS (only 1%) and even decreases in WAS (−3.2%). Under the 4 °C threshold, precipitation is inclined to increase in Asia as a whole and its six sub-regions. In short, accompanied by an increase in the warming thresholds, precipitation also increases overall in Asia but has different regional characteristics. Remarkable increases are mainly found in NAS and CAS, whereas there is little change in WAS where the intermodel range is the largest. The IPCC AR5 (2013) also reports that the projected change of precipitation in WAS is characterized by model scatter. This uncertainty may result from shortcomings in CMIP5 models to simulate interacting dynamical influences on precipitation of the region (IPCC, 2013).

### 3.2. Changes in temperature and precipitation extremes under different warming targets

Fig. 2 shows the probability density of TXx and TNn over six sub-regions under four warming thresholds. Compared with the reference period 1861−1900, with an increase in global temperatures of 1.5−4 °C the probability density curves of TXx over the sub-regions move towards the right side, indicating an increase in the mean value of TXx associated with global warming and more frequent occurrences of very hot and extremely hot weather. The increase in the mean value is most pronounced in WAS; this would seriously impact the local region. In addition, the shape of the curves becomes wider in WAS, EAS, SAS, and SEAS, suggesting an enlargement of the standard deviation of TXx. In particular, there would be an increase in the probability of record-breaking weather occurring in SEAS, despite a relatively small rise in the mean value. The curve shape in NAS and CAS is steep, which implies a more stable increase of TXx (small standard deviation). The uncertainty range under different warming thresholds reveals that a larger uncertainty is generally associated with a higher temperature rise (Fig. 2a), which is consistent with the results of previous study (Zhou et al., 2014).

The change in TNn (Fig. 2b) is approximate with that of TXx. With reference to the period 1861−1900, the TNn probability density curves also shift to the right under different thresholds. This indicates an increase in the mean value of TNn and a decrease in the occurrence of cold weather. Similarly, the curve shape narrows in northern Asia, suggesting a stable increase of TNn and a decrease in the number of cold events. However, the shape in SEAS is wider compared to the other sub-regions, which is indicative of larger variance of TNn in this region.

A comparison between Fig. 2a and b shows that in WAS the shift of TXx towards the right is more apparent than that of

TNn. This implies a higher probability of extremely hot weather in this region. In addition, the CMIP5 projected change in TNn is more consistent than the change in TXx under 1.5−4 °C thresholds; the uncertainty for TNn is smaller than for TXx in the projection.

Fig. 3 shows the probability density distributions of the precipitation extreme indices under 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds. For RX5day (Fig. 3a), except in NAS where the curve moves right (indicating an increase of RX5day), there are no appreciable shifts of the curves in the sub-regions; however, there is an enhanced variance which signifies larger variability in the amount of extreme precipitation. The case under the 1.5 °C threshold resembles that under the other three thresholds, although the uncertainty gradually increases with an increase in the warming thresholds. The changes in R95p (Fig. 3b) show an enhancement in the variance of heavy precipitation in all sub-regions under different warming thresholds. These results show that extreme precipitation will intensify over Asia and the probability of heavy precipitation will increase in the future. In brief, both the order of RX5day and the amount of R95p will tend to increase in a future warmer world.

### 3.3. Differences between 1.5 °C and 2 °C thresholds

Fig. 4 shows differences in mean temperature and precipitation between 1.5 °C and 2 °C thresholds. Compared with the 2 °C threshold, the warming amplitude tends to decrease across the whole of Asia under the 1.5 °C threshold and the temperature is 0.7 °C lower on average; this decrease in the temperature rise is the greatest in NAS (above 1 °C) and the least in SAS and SEAS (about 0.5 °C). Precipitation is reduced by 5%−20% over most of the Asian region under the 1.5 °C threshold, particularly in NAS and CAS. However, an increase of 10%−15% occurs in WAS and western SAS. Overall, precipitation averaged over Asia decreases by 1.5% under the 1.5 °C threshold compared to the 2 °C threshold.

The differences between extreme temperature and precipitation changes in the 1.5 °C and 2 °C thresholds are plotted in Fig. 5, where it is evident that the increase in TXx under the 1.5 °C threshold is at least 0.6 °C lower than that under the 2 °C threshold over most of the Asian region, particularly in NAS and CAS (Fig. 5a). The increase in TNn would be weakened by more than 1.6 °C in CAS, NAS, and western EAS under the 1.5 °C threshold compared to the 2 °C threshold (Fig. 5b). Additionally, there is a uniform reduction in the increasing amplitude of TXx across Asia, while the decline in the increasing amplitude of TNn is relatively larger in mid-high latitudes (particularly in CAS) and relatively smaller in low latitudes.

For precipitation extremes, the RX5day tends to weaken over most of the Asian region under the 1.5 °C threshold compared to the 2 °C threshold, particularly in SEAS

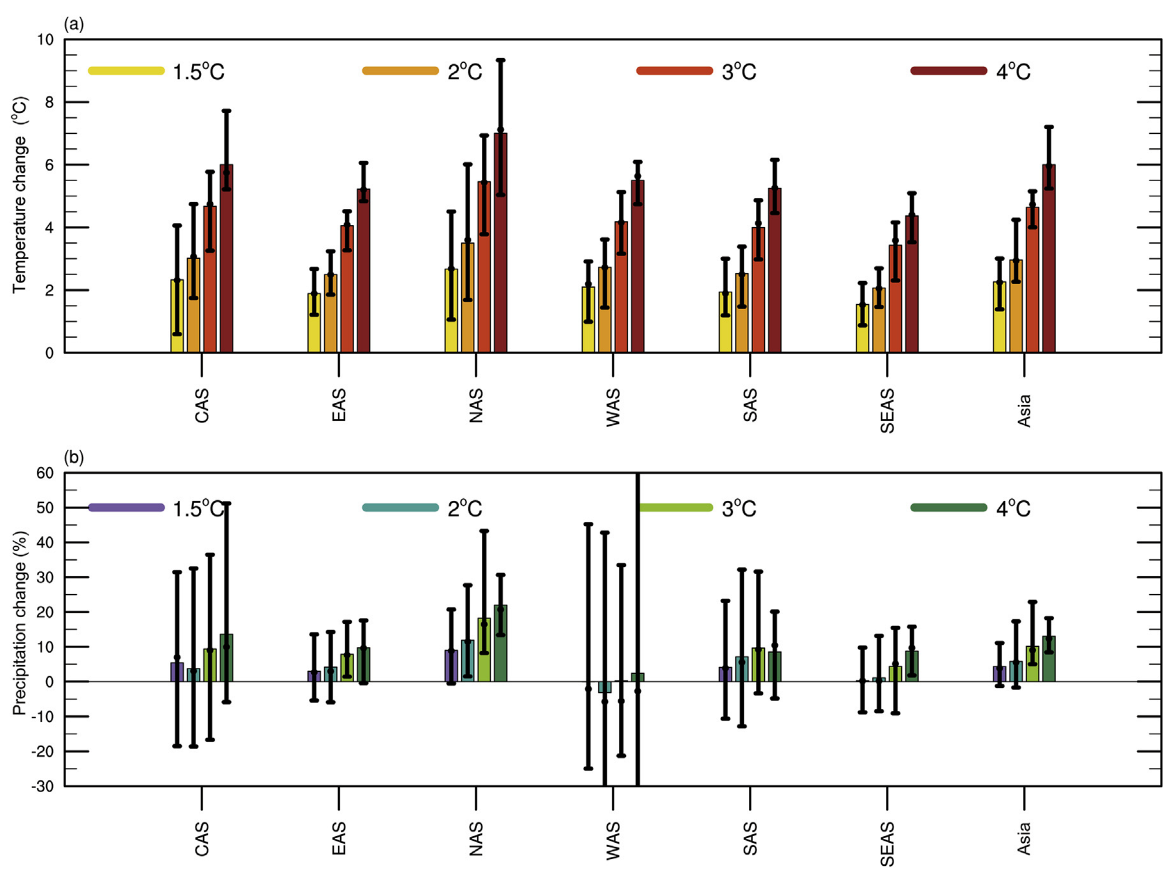


Fig. 1. Changes in temperature and precipitation (relative to 1861−1900) over Asia and its sub-regions under different warming thresholds. The black lines indicate the uncertainty range of models under RCPs and dots show the ensemble median.

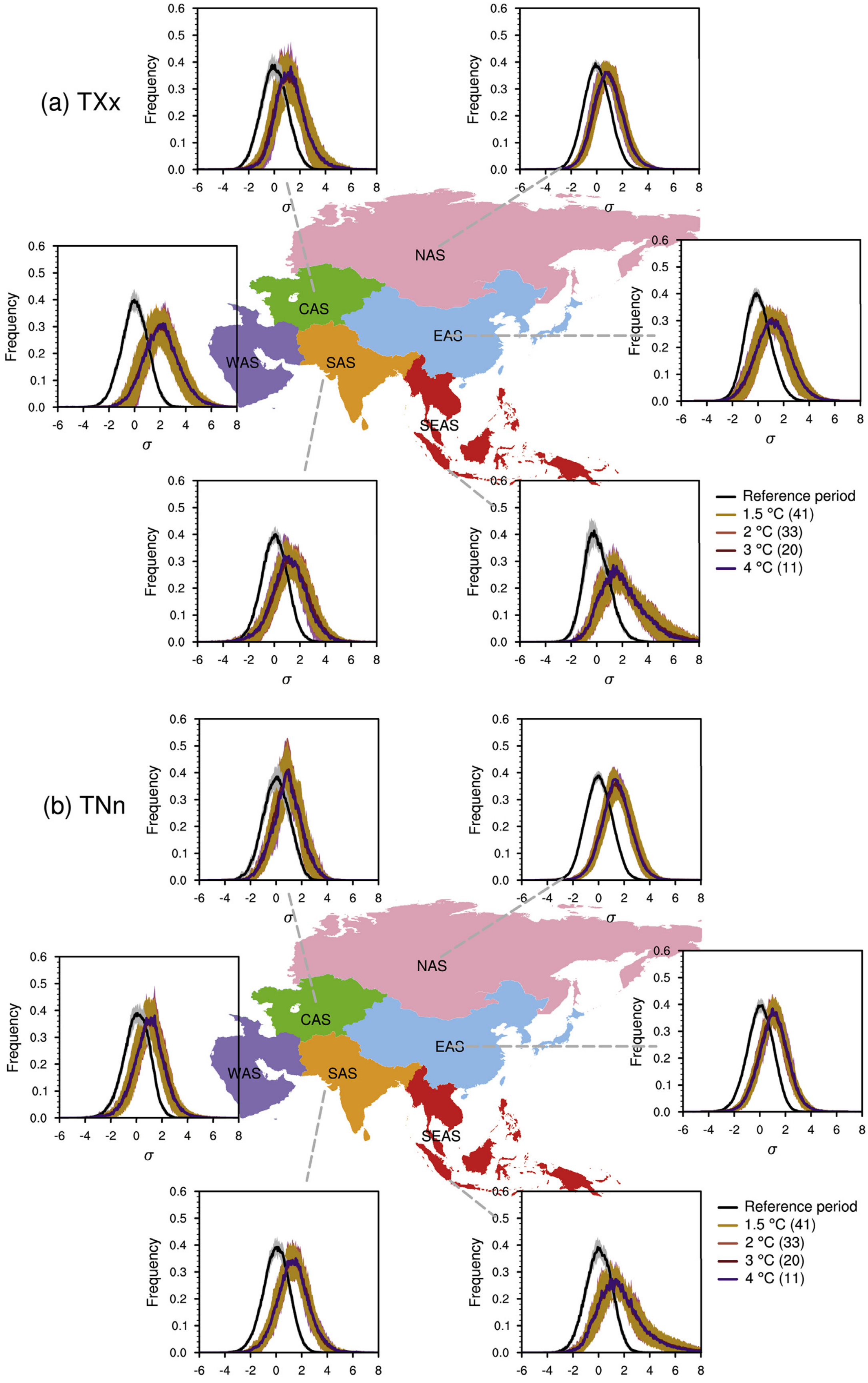


Fig. 2. Probability density distribution of (a) TXx and (b) TNn over Asia (anomaly divided by standard deviation, relative to 1861–1900), where shadings indicate uncertainty range and numbers in brackets indicate the number of total models.

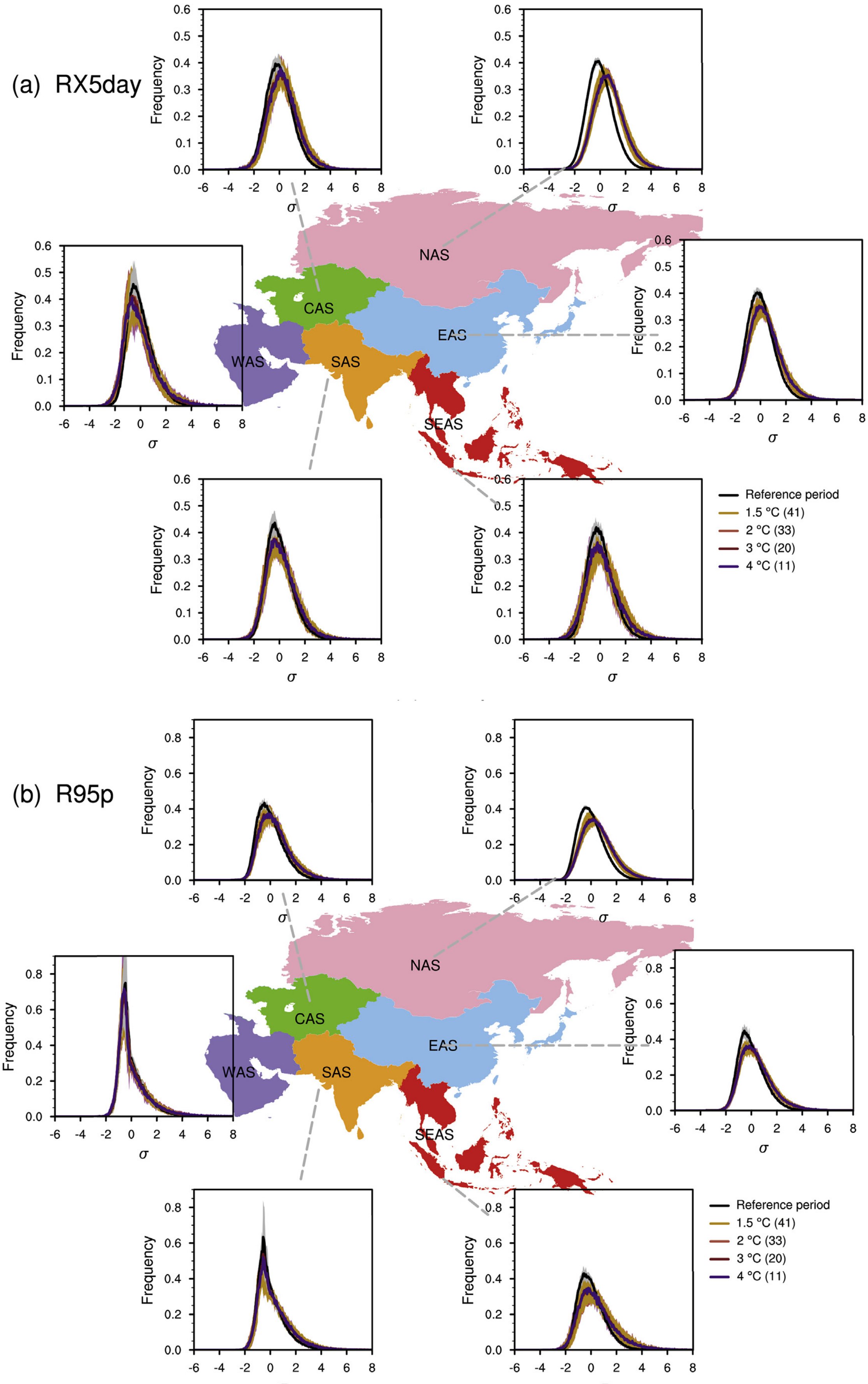


Fig. 3. Same as Fig. 2, but for (a) RX5day and (b) R95p.

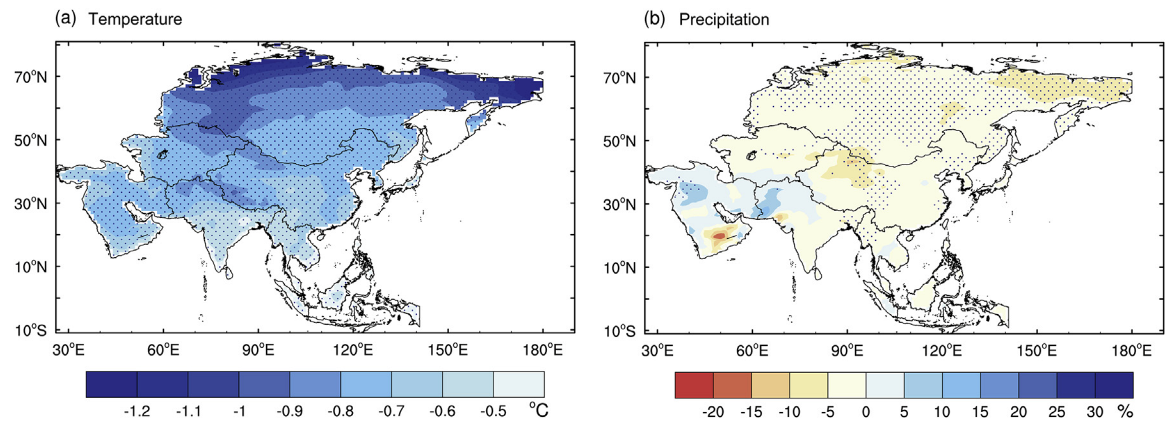


Fig. 4. Differences in (a) temperature and (b) precipitation between 1.5 °C and 2 °C thresholds. Changes above 95% significance level are indicated by dots.

(weakened by about 10 mm); the exception is in WAS and western SAS where a strengthening of RX5day is projected (Fig. 5c). A weakening of R95p is also prominent in SEAS, with a reduction exceeding 50 mm; in contrast, R95p tends to intensify in WAS and western SAS (Fig. 5d).

To further examine changes in extreme temperature and precipitation over the six sub-regions under the 1.5 °C and 2 °C thresholds, Table 4 shows their probability with an absolute value of change larger than 1σ and 3σ. During the reference period 1861−1900, the probability is 20%−40% for the occurrence of very hot (cold) weather over the sub-regions. However, when global temperature warms by 1.5 °C and 2 °C, the probability of very hot weather is increased to 50%−80%; such an increase is the most significant in SEAS and WAS. In contrast, the probability of very cold weather descends to 10%−20%. In addition, no extremely hot or extremely cold weather occurs in Asia during the reference period. If global temperature increases by 1.5 °C, the probability of extremely hot weather will increase generally by 10% in Asia, and by 20% in EAS and WAS. If global temperature increases by 2 °C, the probability of extremely hot weather in WAS will be further enhanced by 10%, and no extremely cold weather will occur in Asia.

For extreme precipitation, relative to the reference period the probability of RX5day larger than 1σ will increase by 10% under the 1.5 °C and 2 °C thresholds over the sub-regions

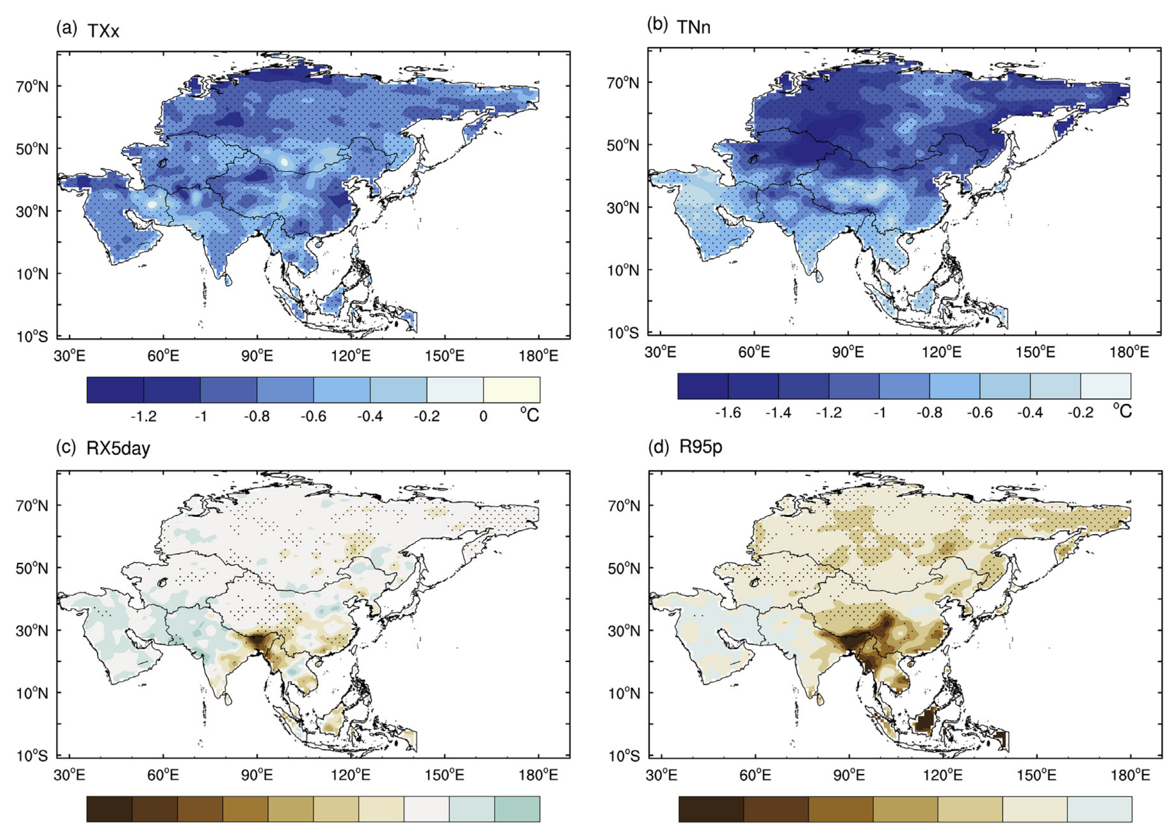


Fig. 5. Same as Fig. 4 but for (a) TXx, (b) TNn, (c) RX5day, and (d) R95p.

Table 4
Probability of temperature and precipitation extremes under 1.5 °C and 2 °C thresholds.

| Region | | 1861−1900 | | | | 1.5 °C | | | | 2 °C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TXx | TNn | RX5day | R95p | TXx | TNn | RX5day | R95p | TXx | TNn | RX5day | R95p |
| ≥1σ (%) | CAS | 30 | 40 | 30 | 20 | 60 | 20 | 40 | 40 | 60 | 20 | 40 | 40 |
| | EAS | 30 | 40 | 30 | 20 | 60 | 20 | 40 | 30 | 60 | 20 | 40 | 30 |
| | NAS | 30 | 30 | 40 | 30 | 50 | 10 | 40 | 40 | 50 | 10 | 40 | 40 |
| | SAS | 30 | 30 | 20 | 20 | 60 | 20 | 30 | 30 | 60 | 10 | 30 | 30 |
| | SEAS | 20 | 40 | 20 | 20 | 70 | 10 | 30 | 30 | 70 | 10 | 30 | 30 |
| | WAS | 30 | 40 | 20 | 20 | 80 | 10 | 30 | 30 | 80 | 10 | 30 | 30 |
| ≥3σ (%) | CAS | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 10 | 10 | 0 | 10 | 10 |
| | EAS | 0 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 0 | 0 | 10 |
| | NAS | 0 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 0 | 10 | 10 |
| | SAS | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 10 | 10 | 0 | 0 | 10 |
| | SEAS | 0 | 0 | 0 | 0 | 20 | 20 | 0 | 10 | 20 | 0 | 0 | 10 |
| | WAS | 0 | 0 | 0 | 0 | 20 | 10 | 0 | 10 | 30 | 0 | 0 | 10 |

(except NAS). However, the probability of RX5day being larger than 3σ only appears in NAS and EAS under the 1.5 °C threshold, but appears in NAS and CAS under the 2 °C threshold. The probability of the R95p exceeding 1σ is the same for both the 1.5 °C threshold and the 2 °C threshold, which is more than 10% higher than the reference period, but the probability of the R95p exceeding 3σ will increase by 10% across all sub-regions.

## 4. Conclusions and discussion

Using simulations from 18 CMIP5 models under three RCP scenarios, we comprehensively analyze changes of temperature and precipitation and their extremes over Asia under 1.5−4 °C warming targets. The difference in Asian climate change in response to the 1.5 °C and 2 °C warming targets is further investigated and the main findings are summarized as follows:

(1) Relative to the pre-industrial era, under 1.5 °C, 2 °C, 3 °C, and 4 °C thresholds the mean temperature averaged over Asia will increase by 2.3 °C, 3.0 °C, 4.6 °C, and 6.0 °C, respectively. In addition, Asian precipitation will increase by 4.4%, 5.8%, 10.2%, and 13%, respectively. In general, concurrent with enhancement of the warming thresholds, there will be a gradual increase in temperature, with a larger response in high latitudes than in mid-low latitudes. Precipitation will also increase but with apparent regional features.

(2) Under 1.5−4 °C thresholds, the mean value and variance of TXx and TNn will strengthen, indicating more frequent very hot weather and less frequent very cold weather. Extreme heavy precipitation will intensify and the variance in the amount of extreme precipitation amount will enlarge. However, there may be more uncertainty in general in the projection as the warming thresholds increase. In addition, compared with the mean temperature and precipitation, changes in extreme temperature and precipitation are more significant.

(3) Compared with the mean climate under the 2 °C threshold, under the 1.5 °C threshold the mean temperature will be lower by 0.5−1 °C over Asia. The precipitation will be less by 5%−20% over most Asian regions, particularly in NAS and CAS, but will be greater by 10%−15% in WAS and western SAS.

(4) Compared with climate extremes under the 2 °C threshold, under the 1.5 °C threshold the TXx will be cooler uniformly across Asia. In addition, the warming in TNn will also decrease, which is most evident in high latitudes, particularly in CAS. The RX5day and R95p will be weaker over most Asian regions, but will be stronger in WAS and western SAS.

(5) With respect to the reference period 1861−1900, the probability of very hot weather occurring in Asia will at least double, and that of very cold weather will decrease by 1−2 times under both the 1.5 °C and 2 °C thresholds. The probability of extremely hot weather will increase generally by 10% over Asia, and by 20% in SEAS and WAS under the 1.5 threshold. However, if global temperature rise reaches 2 °C, the probability of extreme hot weather will increase by a further 10% in WAS. In addition, the probability of extreme heavy precipitation will increase by 10% over Asia under both the 1.5 °C and 2 °C thresholds.

In summary, the increasing amplitude of temperature over Asia is greater than that of the global average change under the different warming thresholds. The change in precipitation is very complicated and shows different regional characteristics. There is a higher probability of extremely hot weather and extreme heavy precipitation, and a lower probability of extremely cold weather in the future. The projection uncertainty tends to increase in response to higher warming thresholds. It is of note that these results are based on a multi-model ensemble using multi-scenarios conducted with various amplitudes of global temperature increase as the criterion. In fact, when the rise in global temperature reaches the differing warming thresholds under various greenhouse gas emission scenarios, changes in temperature over different regions are in accordance with the scenarios: using the same warming threshold, warming regions have a different response to different greenhouse gas emission scenarios (Chen et al., 2015; Chen and Zhou, 2016).

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